# OIL-FREE FOIL BEARINGS FOR PROPULSION AND POWER GENERATING GAS TURBINE ENGINES: MESOSCOPIC TO MACROSCOPIC SCALE

James F. Walton II
Member ASME
Mohawk Innovative Technology, inc.

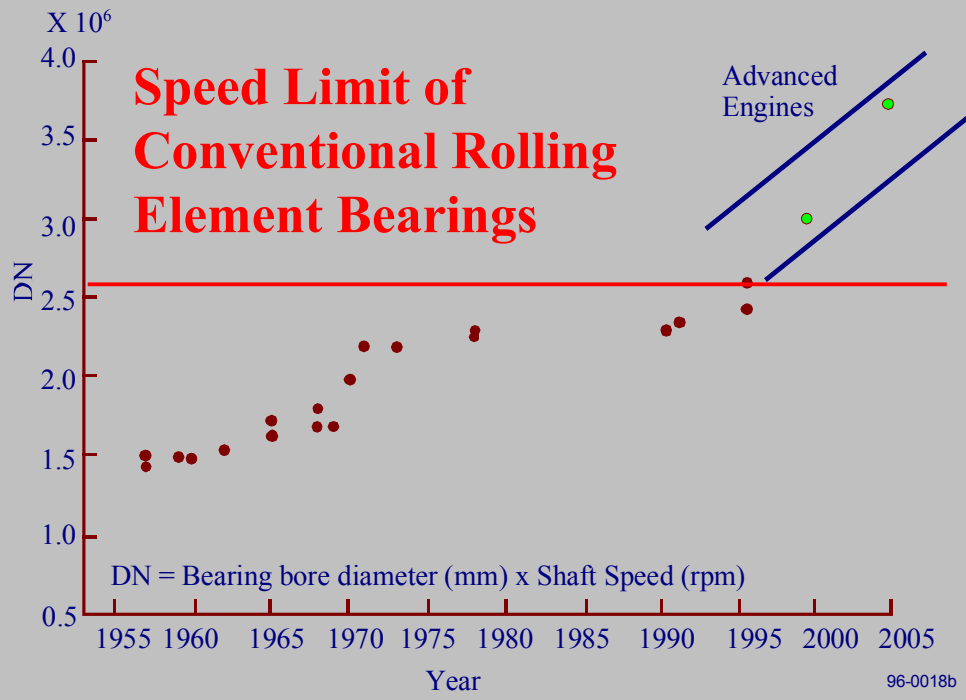
ASME TurboExpo 2003
June 19, 2003

# Overview

- Introduction
  - Background and Trends
- Macro scale – 150 mm foil bearing
  - Experimental test rig
  - Test results
- Gas Turbine Test
- Mesoscopic oil-free turbojet simulator
  - Components
  - Application
  - Rotor dynamic analysis, Alternative bearing support
  - Test results
- Conclusion/Remarks

# Introduction

- Machinery Trends
  - Higher Power Density
  - Higher Efficiency
  - Smaller Footprint
  - Environmentally Conscientious
  - Higher Speeds
  - Higher Temperatures
  - Longer Maintenance Cycles
- Technology Advances
  - High Speed Air Bearings
  - High Speed Integral Motors and Drives
  - S-o-A Aero




- 25-50% of All Gas Turbine Maintenance Attributed to Bearing & Lube System
  - Oil, Tank, Pump, Filter
  - Air Breather Tubes
  - Plumbing/Scavenge Lines, Internal Flow Passages
  - Lubrication Oil/Fuel Jets, etc…

# Foil Bearing Technology Advantages

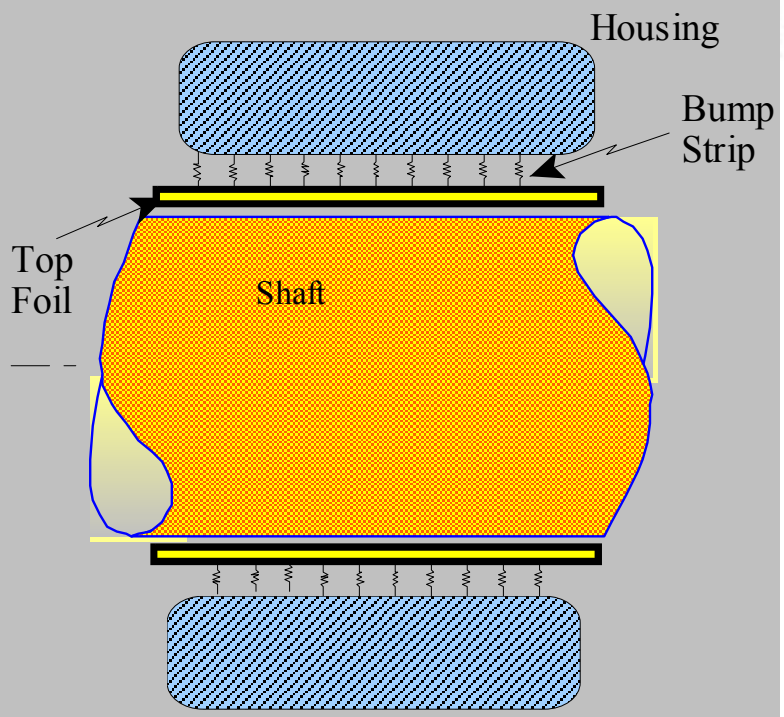
MOHAWK INNOVATIVE TECHNOLOGY, INC.

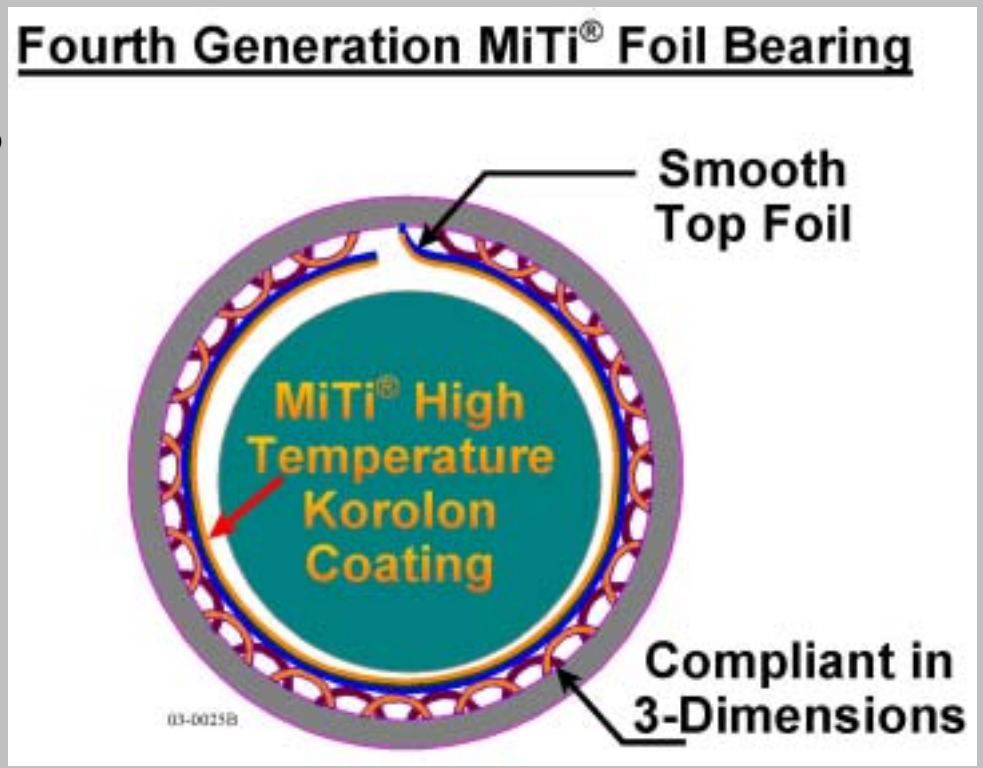
- Eliminates Many Maintenance Items
  - Oil lubrication supply system and plumbing lines
  - Oil Filter
  - Oil Cooler
  - Breather Tubes
- Greater Power Density
  - Very High-Speed
  - High Temperature
  - Low Power Loss Especially for Smaller Engines
- Indefinite Storage for Unmanned Applications

# Foil Bearing Design & Operation

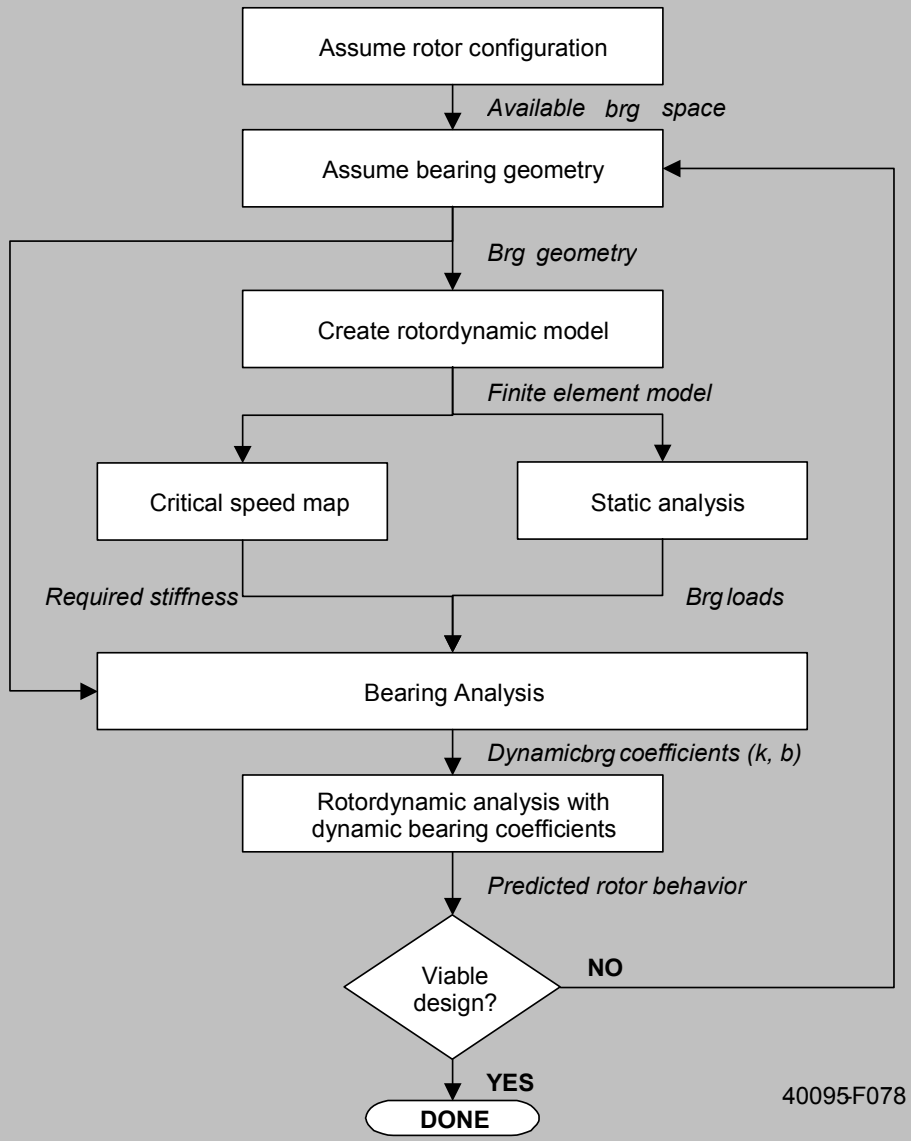
Air bearings consist of a compliantly mounted smooth inner top foil. During operation there is no contact between shaft and bearing.

- The Smooth Top Foil Provides the Surface for Generating Hydrodynamic Pressures Which Provide Lifting Forces to Separate the Shaft and Bearing
- The Compliant Elements Provide Structural Stiffness and Damping and Accommodate Journal Thermal Growth, Centrifugal Growth and Misalignment



# Design Approach




40095-F078

## Reynolds Equation with Turbulence Functions

$$\frac{\partial}{\partial\theta}\left[G_x p^*(h^*)^3\frac{\partial p^*}{\partial\theta}\right]+\frac{\partial}{\partial z^*}\left[G_z p^*(h^*)^3\frac{\partial p^*}{\partial z^*}\right]=\Lambda\frac{\partial}{\partial\theta}\left(p^*h^*\right)$$

$$h^*=\left(\frac{h}{C}\right)=1+e\ \cos(\theta-\phi)+\sum\alpha_{i,j}(p^*-1)$$

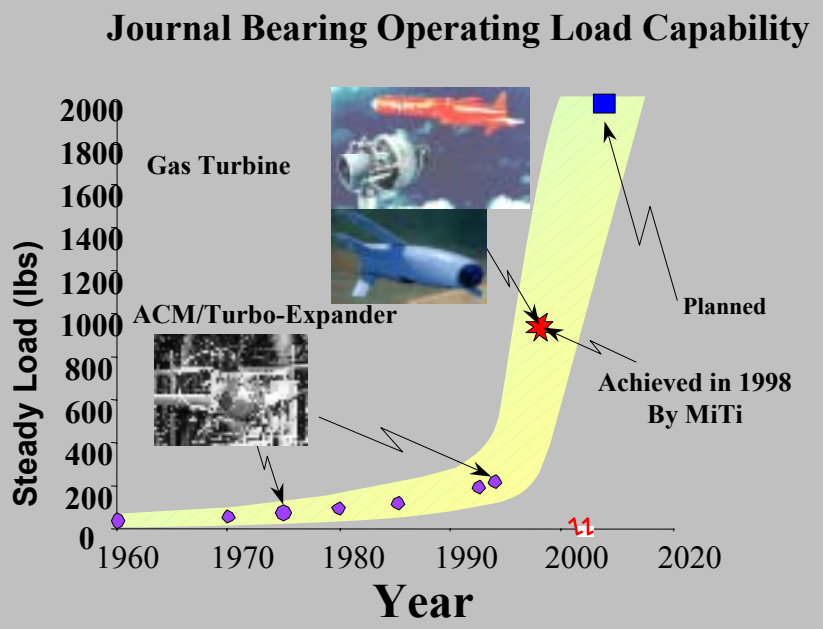
$$h^*=\left(\frac{h}{C}\right)=1+e\ \cos(\theta-\phi)+\sum\alpha_{i,j}(p^*-1)$$

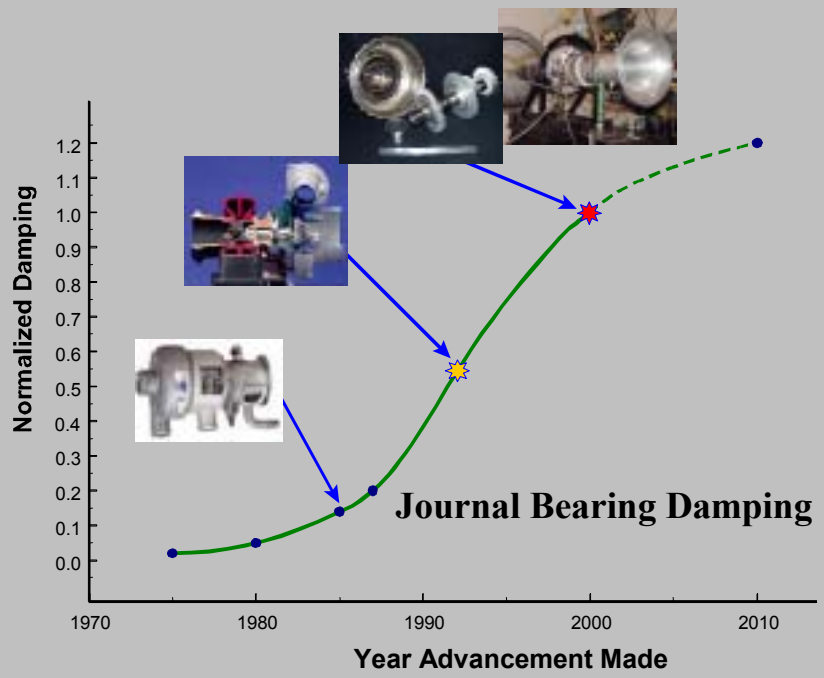
$$|\nabla p|^*=\left(\left(\frac{\partial p^*}{\partial\theta}\right)^2+\left(\frac{\partial p^*}{\partial z^*}\right)^2\right)^{1/2},\qquad \mathrm{Re}^*=\mathrm{Re}_r{}^*(h/C)^3|\nabla p|^*$$

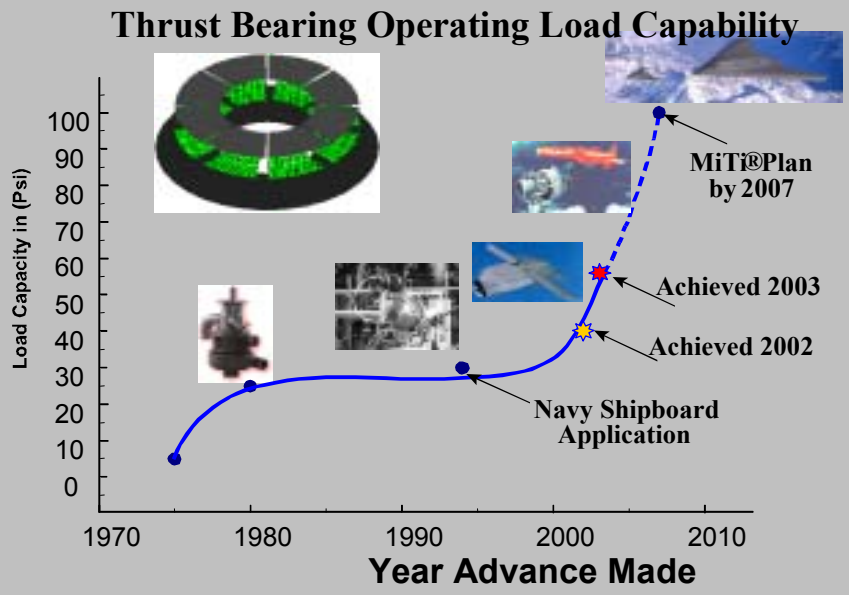
# Design Issues

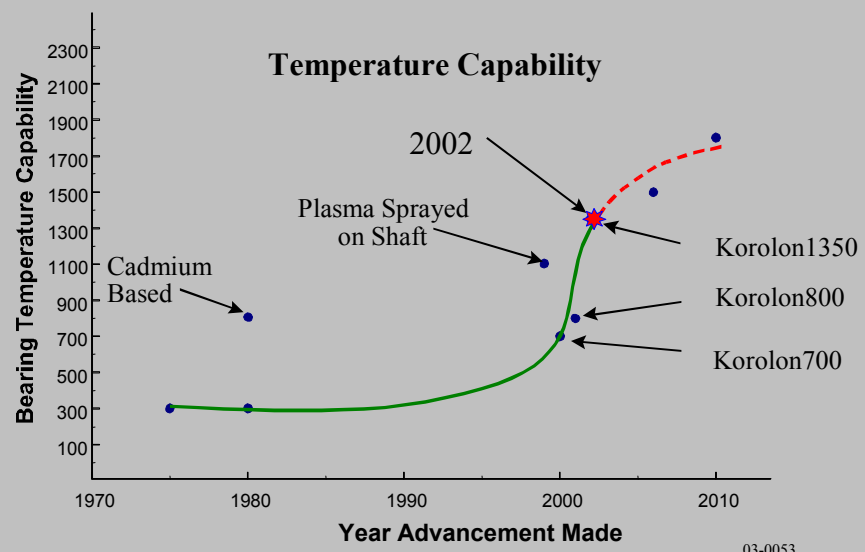
- Total Load Carrying Ability and Size
  - Static
  - Dynamic
- Rotor-Bearing System Dynamics
  - Stiffness
  - Damping
  - Location Relative to Node
- Thermal
  - Maximum Operating Temperature
  - Stability and Cooling Flow Required
  - Power Loss
- Environment
  - Working Gas
  - Debris
  - Duty Cycle (i.e., starts and stops)

# Foil Bearing Capabilities



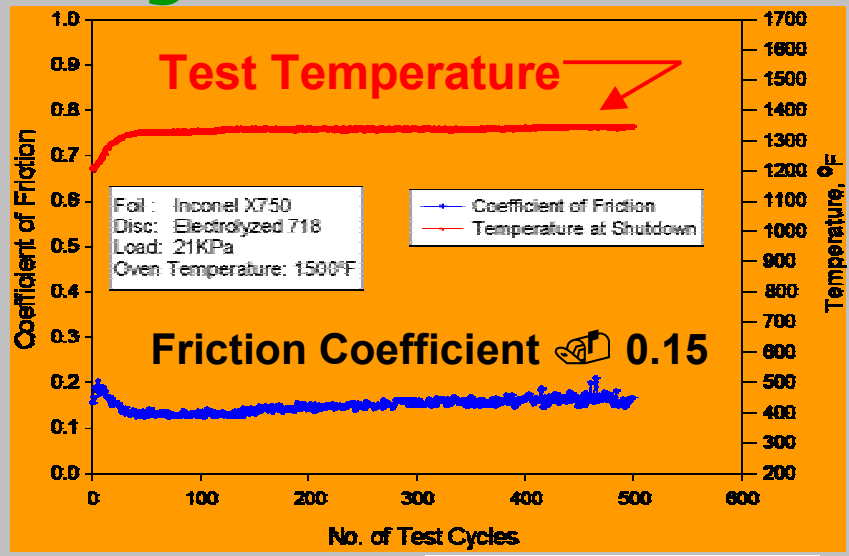



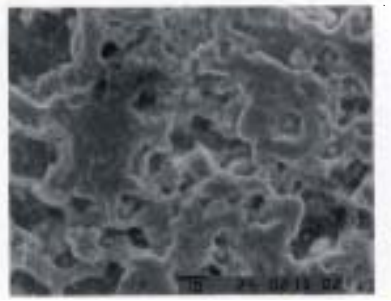
# Korolon 1350A & B Coatings

Coating Thickness 0.0002 - 0.001” (5-25 m)

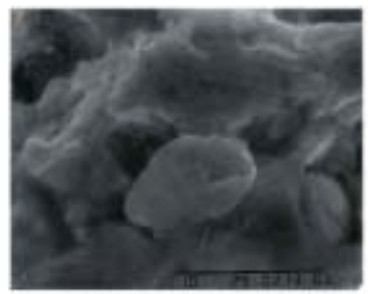
Surface Finish 2-10 in Ra (0.05 - 0.25 m)

Service Temperatures to 1350°F (730°C)

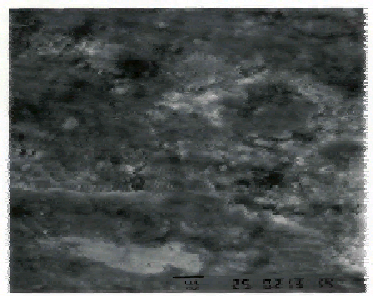


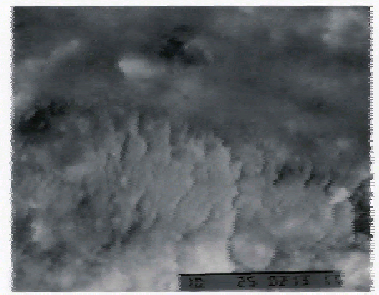
Before Test - X1000



Before Test - X5000



After Test - X1000



After Test - X5000

Flat Plate Like Particle Deposition

Low Porosity – Dense Coating

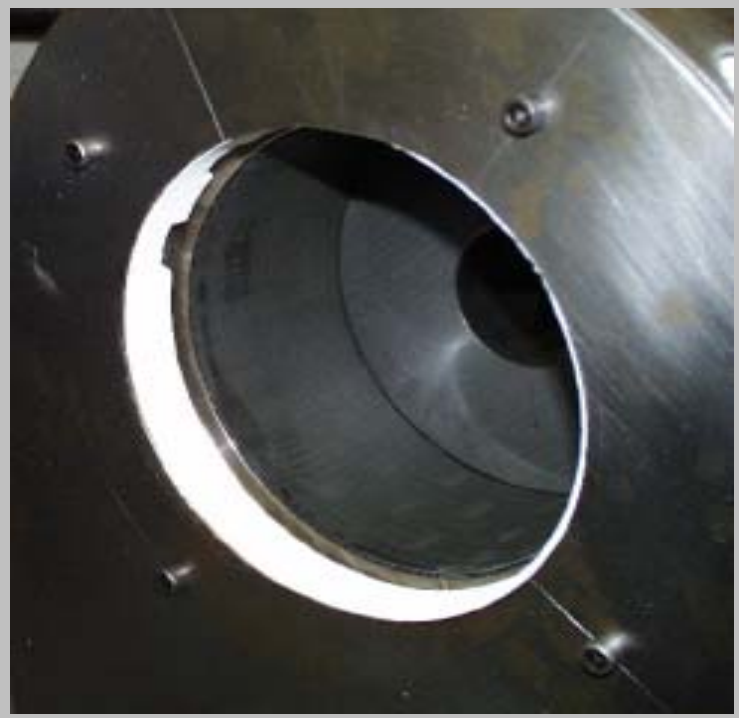
Surface Smearing Indicates Possible Ductility

May Contribute to the Low Friction Coefficient

# Macro scale – 150 mm foil bearing

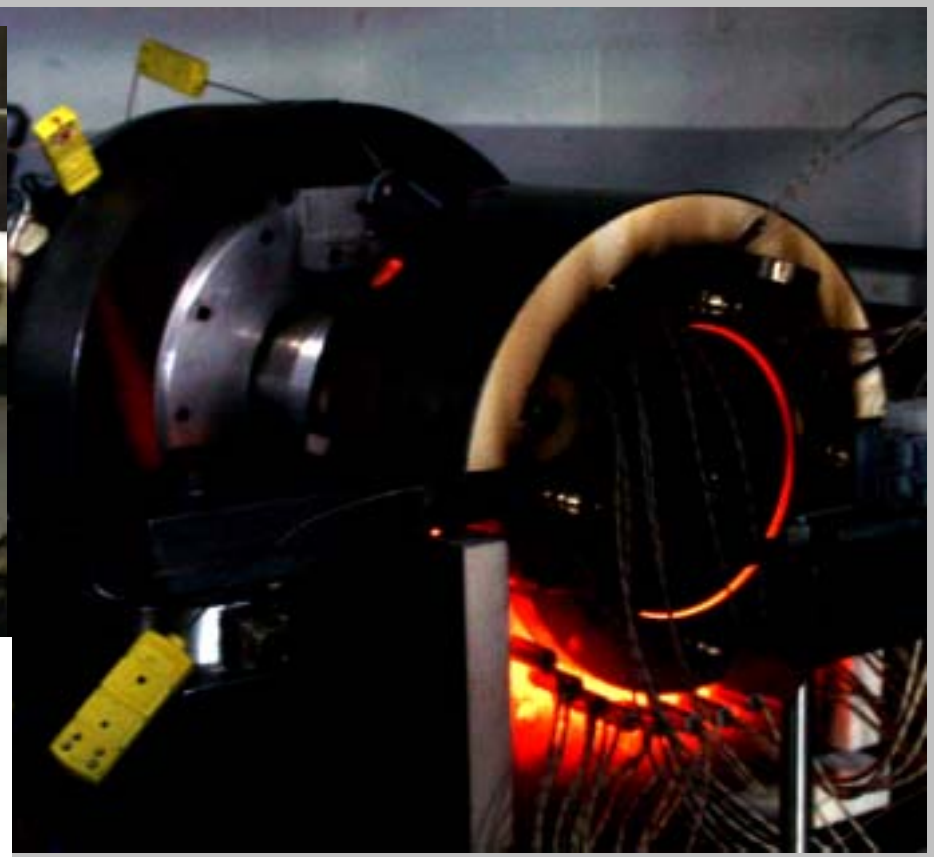
MOHAWK INNOVATIVE TECHNOLOGY, INC.

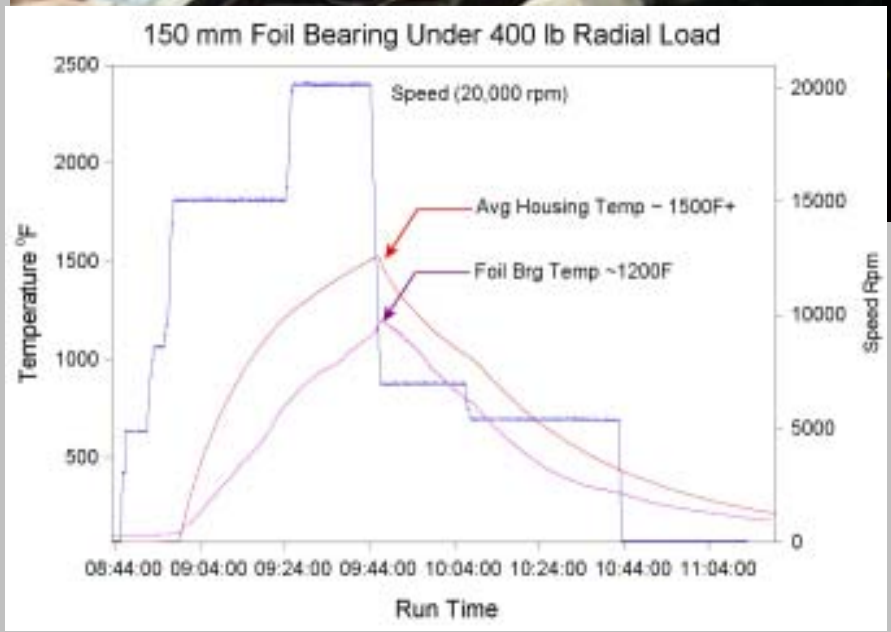
150 mm Foil Bearing with Korolon Coating



Hollow Rotor with Hard Chrome Coating after High Temperature Testing

# 150 mm Bearing at 1200F



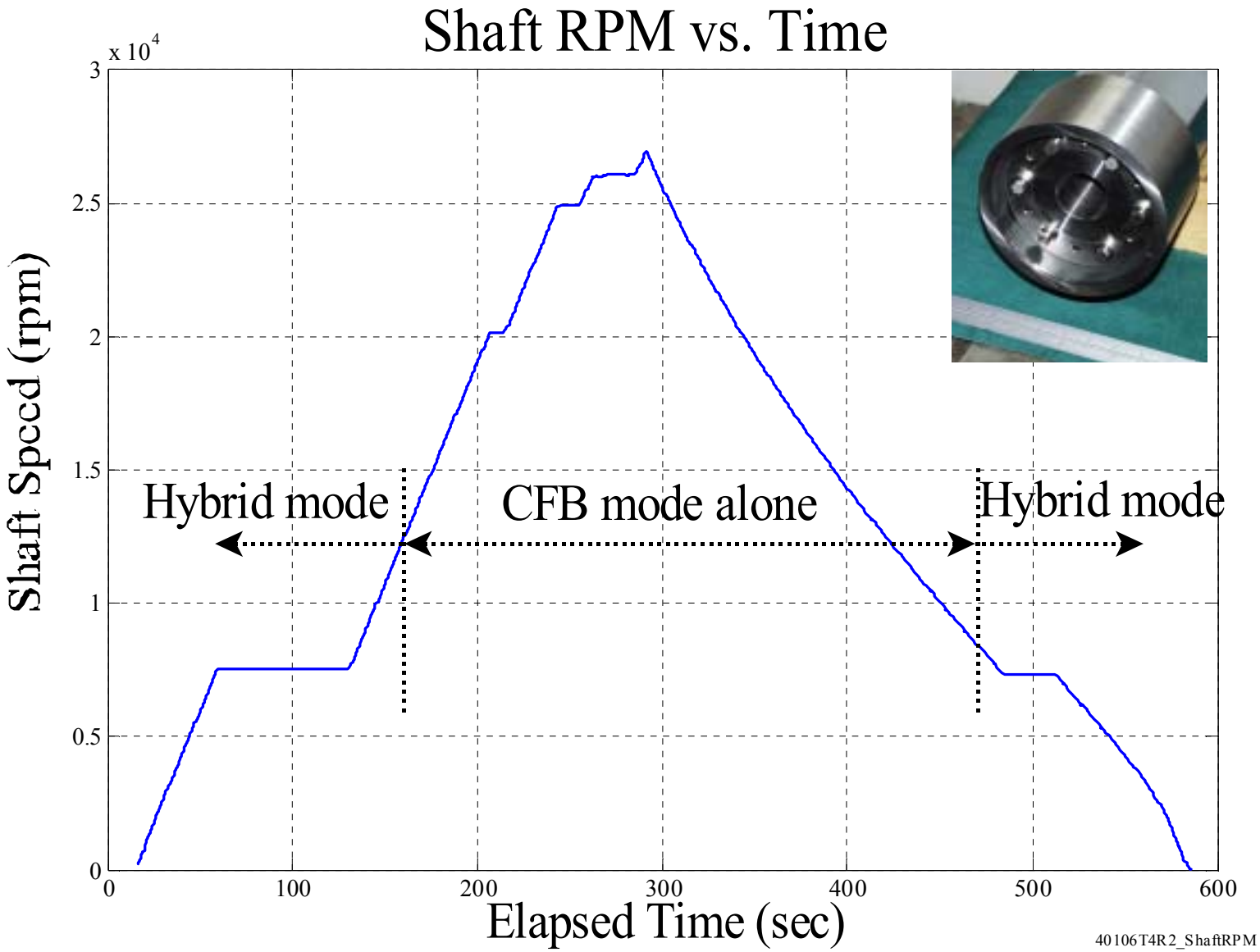



**Operated to 27,500 rpm (4.05 MDN)**

**Maximum Ambient Temperature to date 1500F**

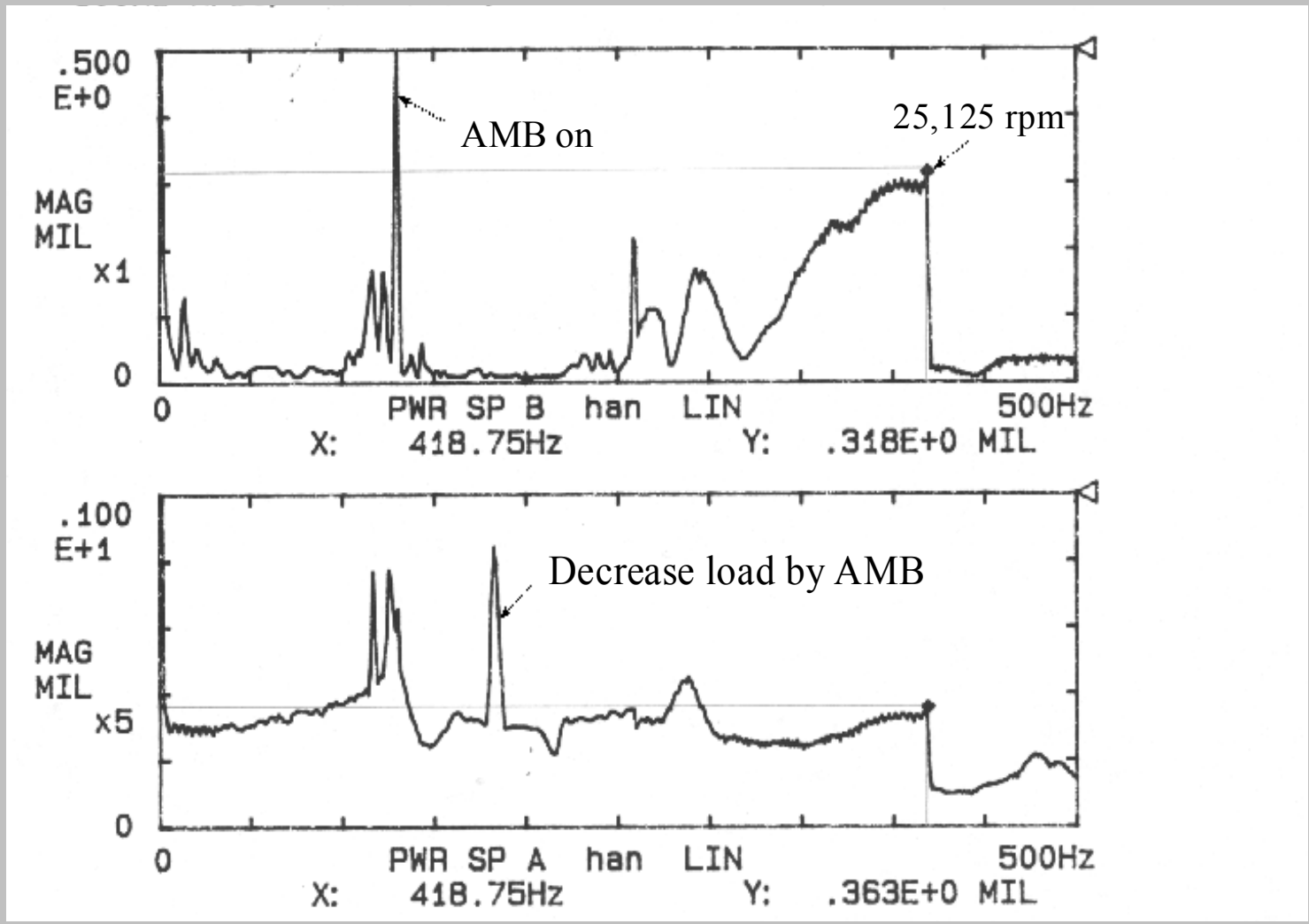
**120 lb Rotor Weight**

# Test Results – 150 mm foil bearing

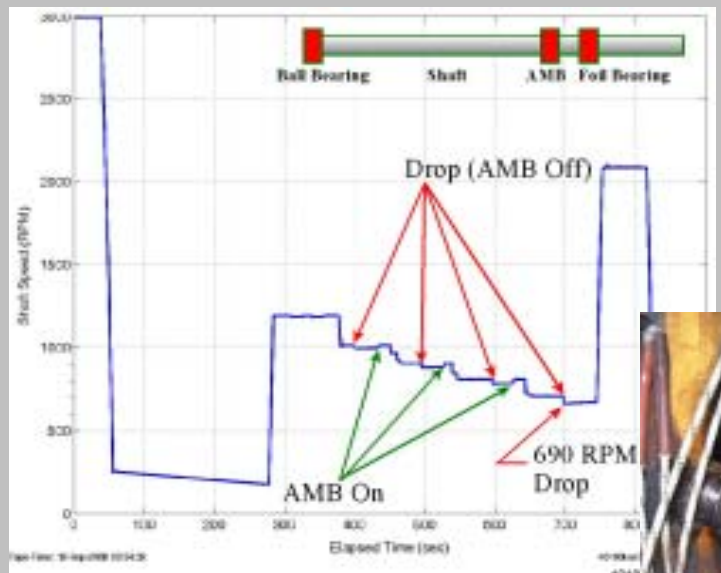


# Test Results – 150 mm foil bearing (contd)

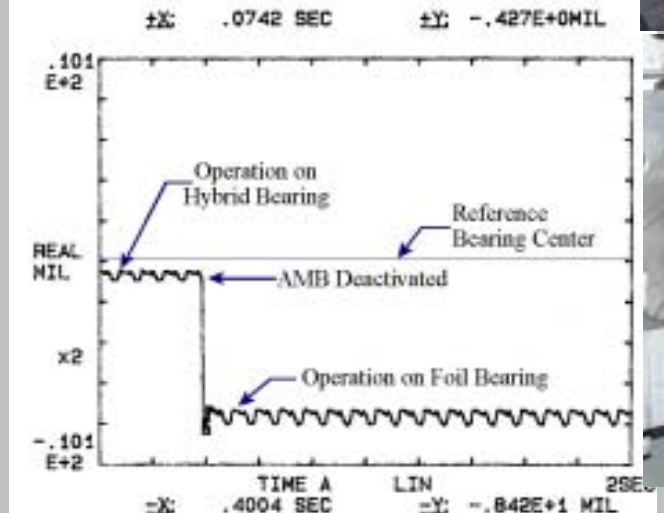
Ambient temperature

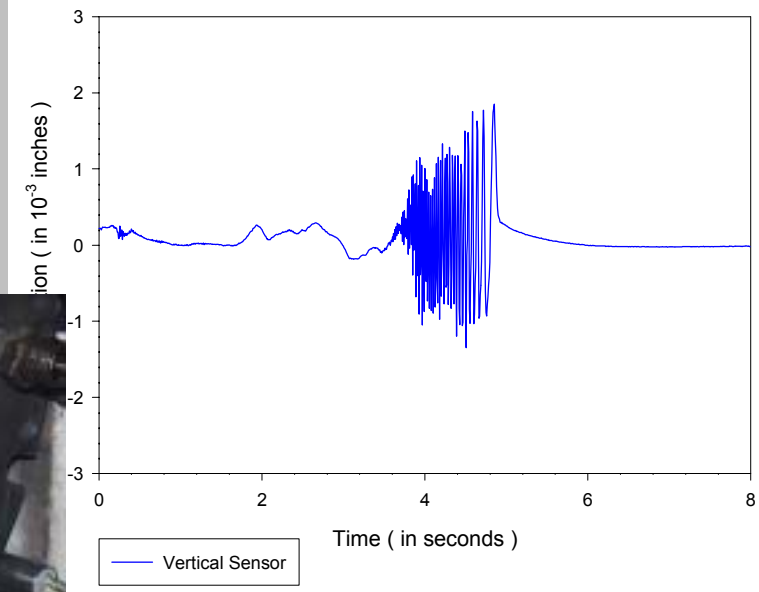


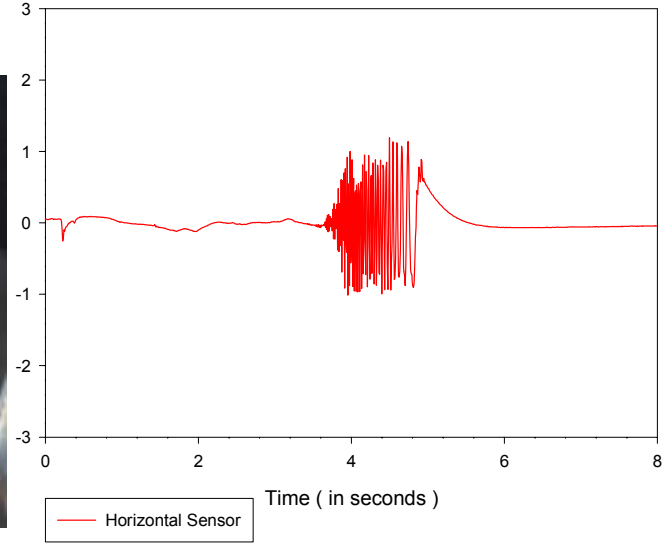
# 150 CFB Transient Tests



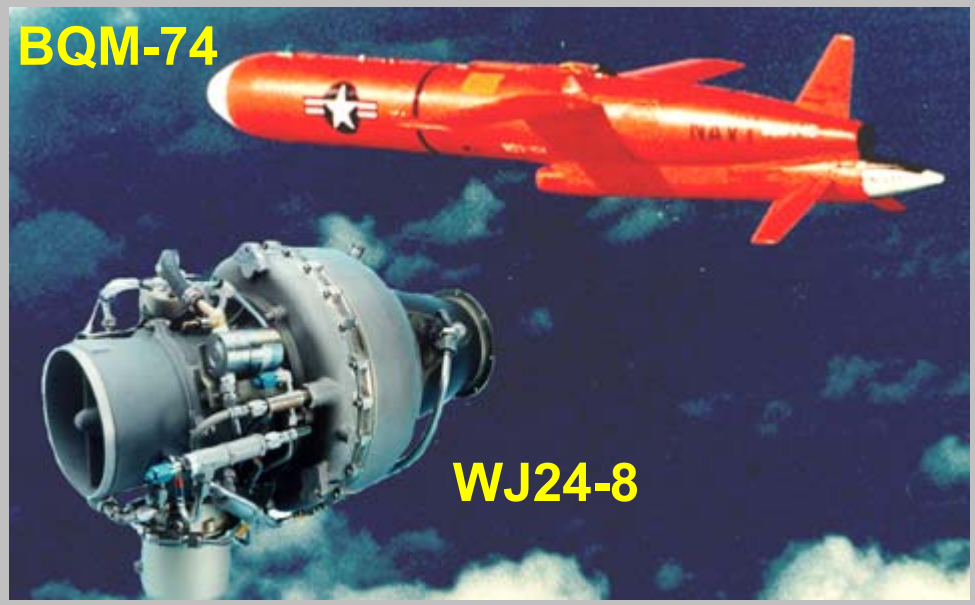

106 HYBRID FOIL MAG 700 RPM DROP 9/12/02
200Hz A: DC/0.5V B: AC/ 50V INST 0/16 DUAL



# Test of Oil-Free Engine




**WJ24-8, 240 lb Thrust Engine**

**Over 14 hours Operation**

**70 Start Stop Cycles**

**7 Simulated Mission Cycles**

•

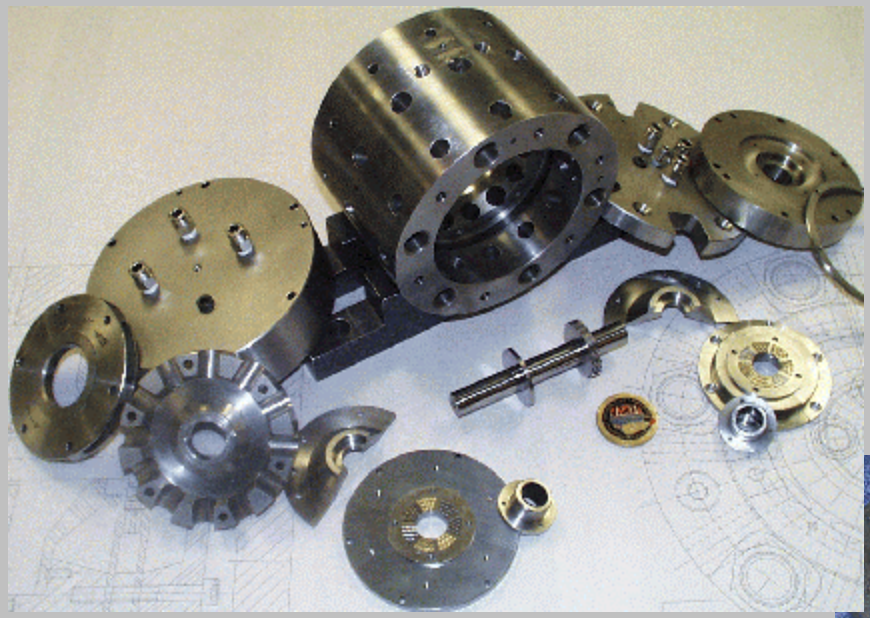
**Hot Section Rolling Element Bearing Eliminated**

**Oil Mister Eliminated**

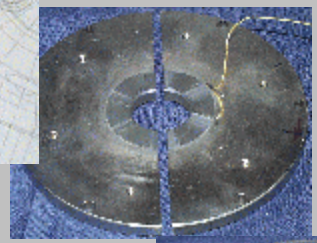
**~ Cost/Weight Reductions to 20%**

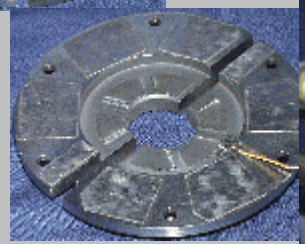
**Increased Life and Performance**

# Small Rotor-Bearing Simulator



Test Rig, Rotor and Both Journal and Thrust Bearings



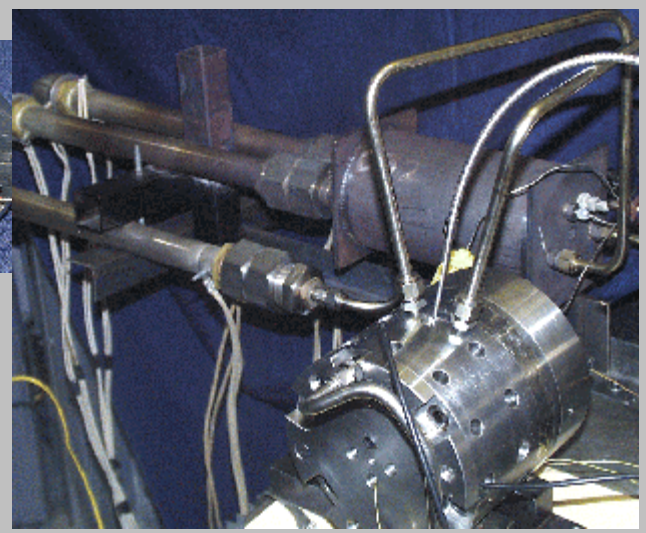


Split Thrust Bearings

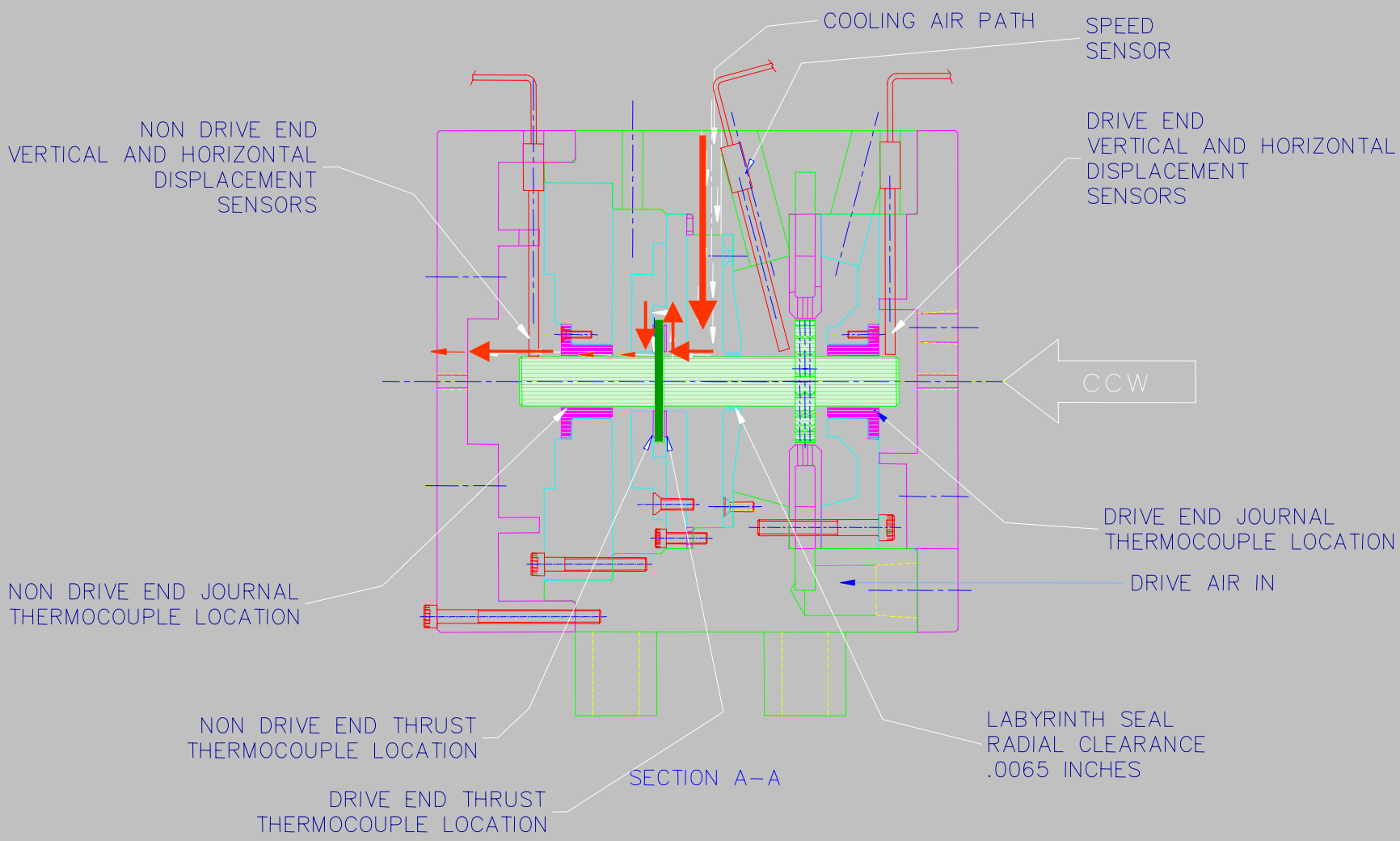
One of a Kind Split Thrust Foil Bearings for Exotic Material Systems

Totally Oil-Free Simulator
Tested to 500+F
and
150,000 rpm (115% Speed)

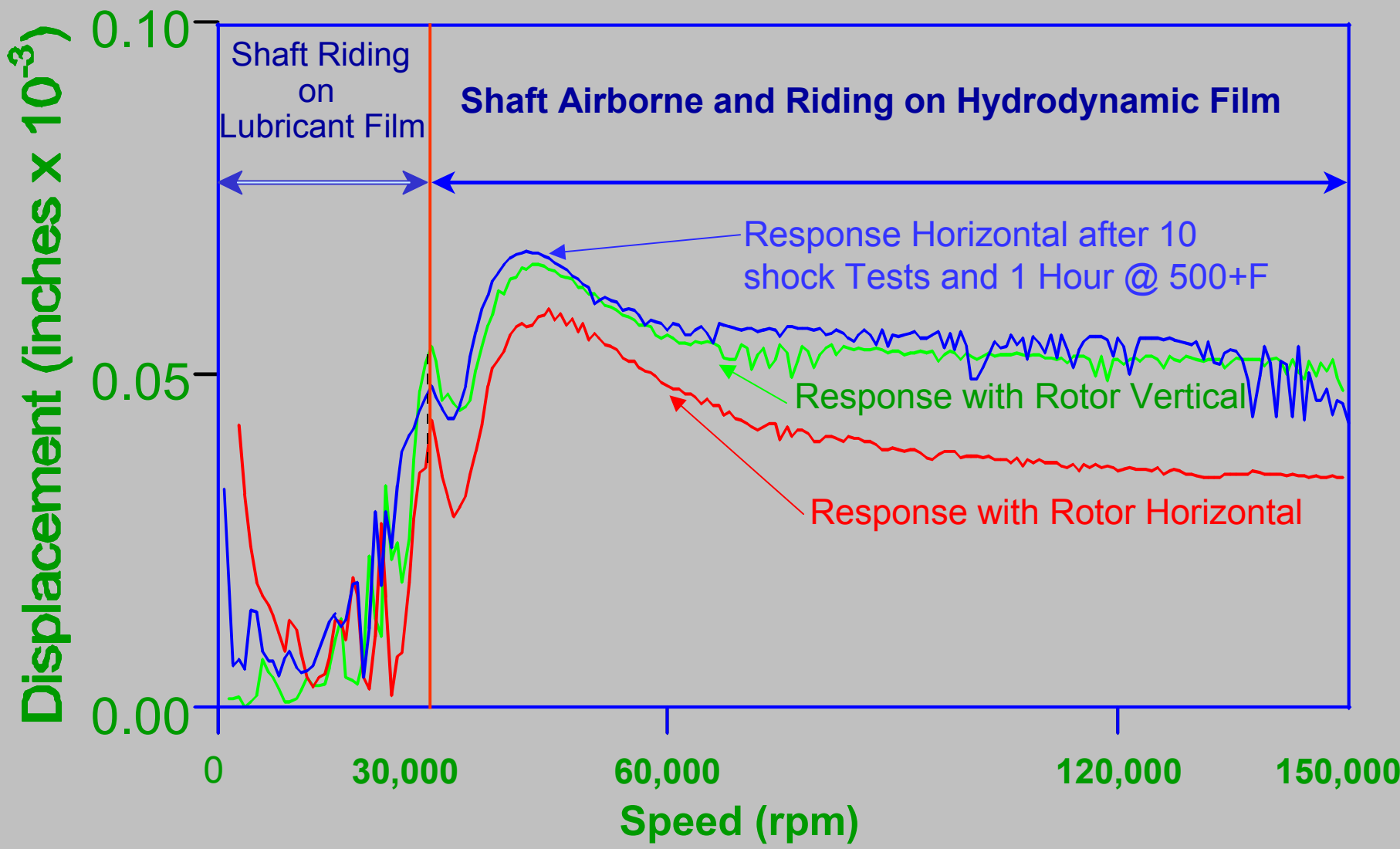
Assembled Test Rig and High Temperature Inlet Air



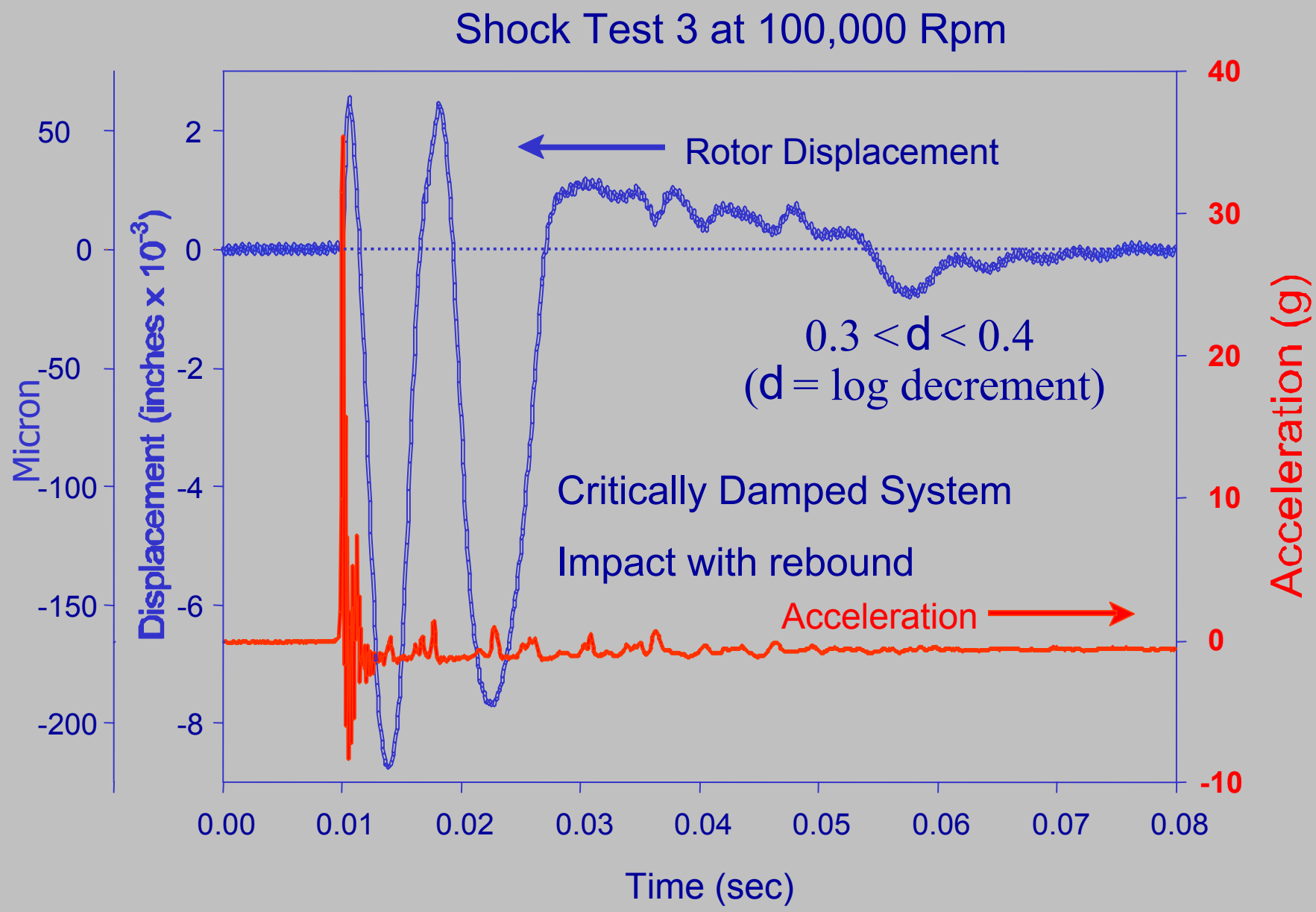
# High Temperature Test Setup



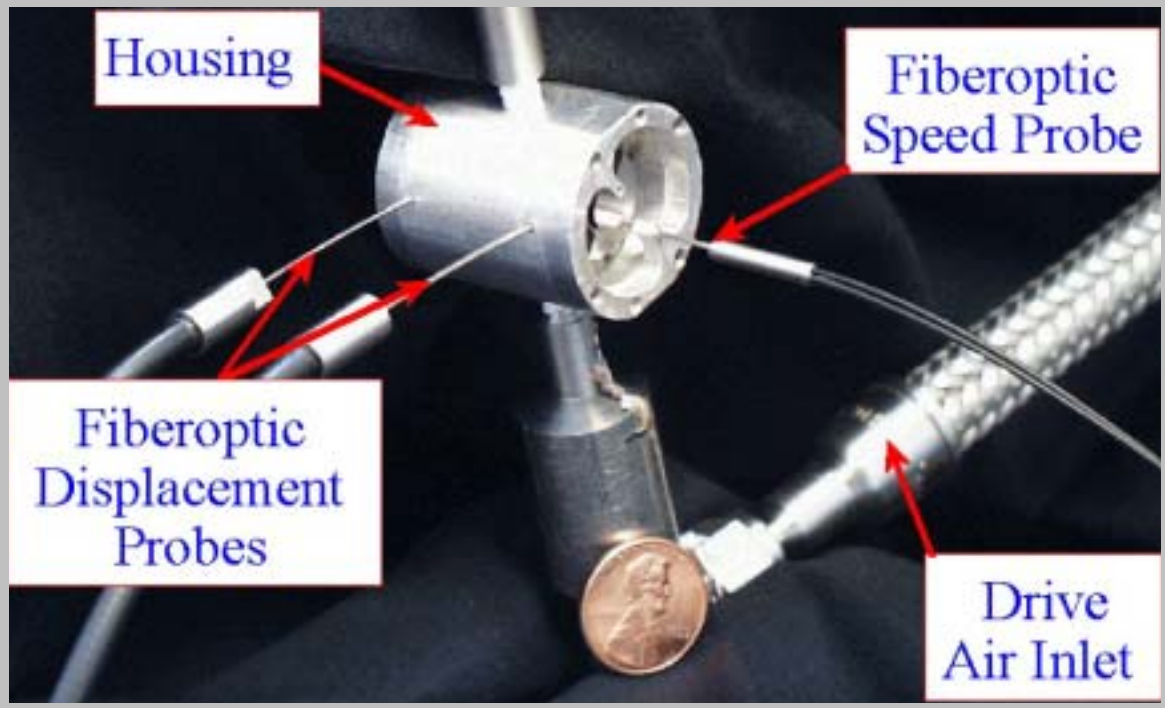
# Peak Vibration Comparisons



# Example Impact Shock Test



# Mesoscopic oil-free turbojet simulator

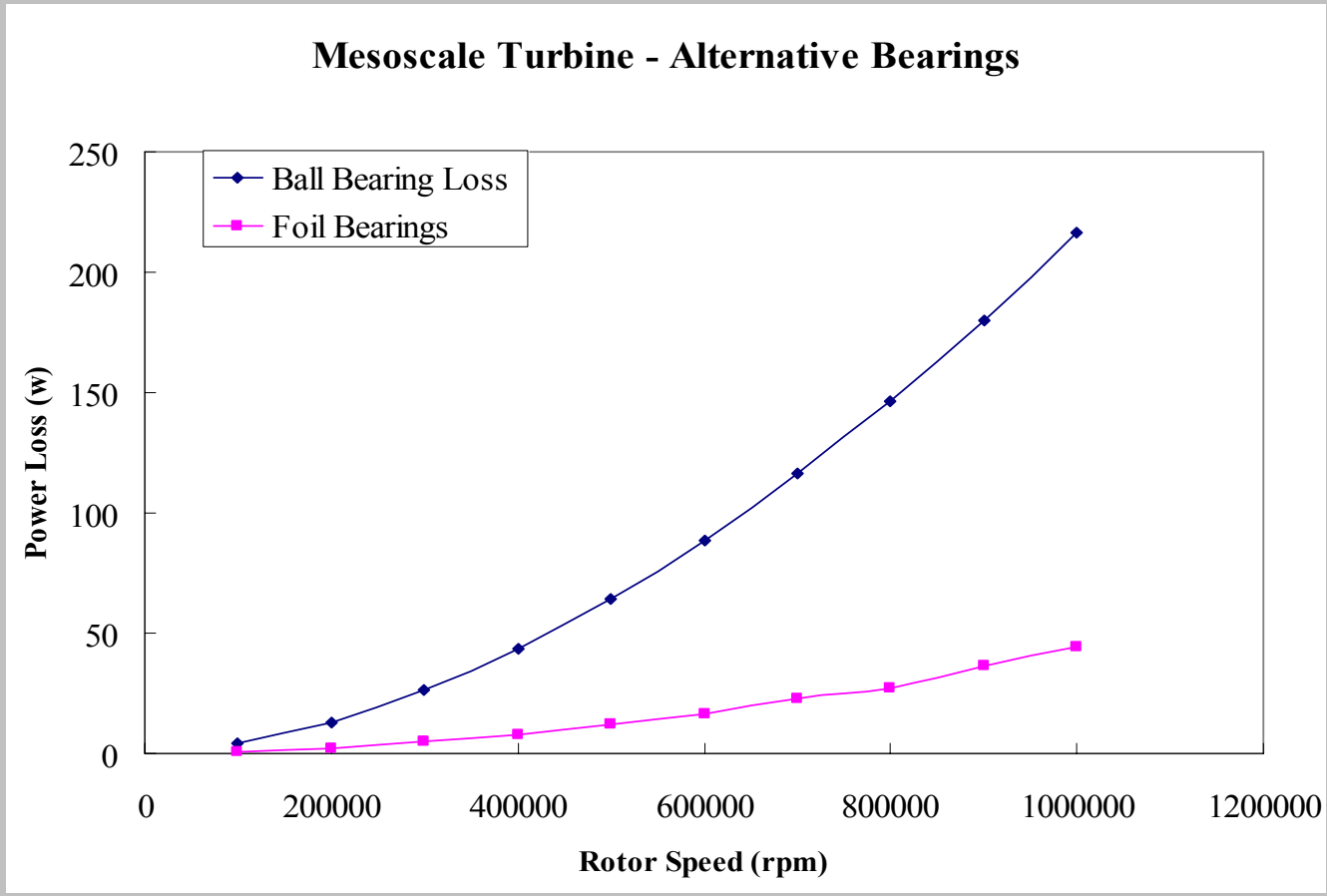



Horizontal operation

G

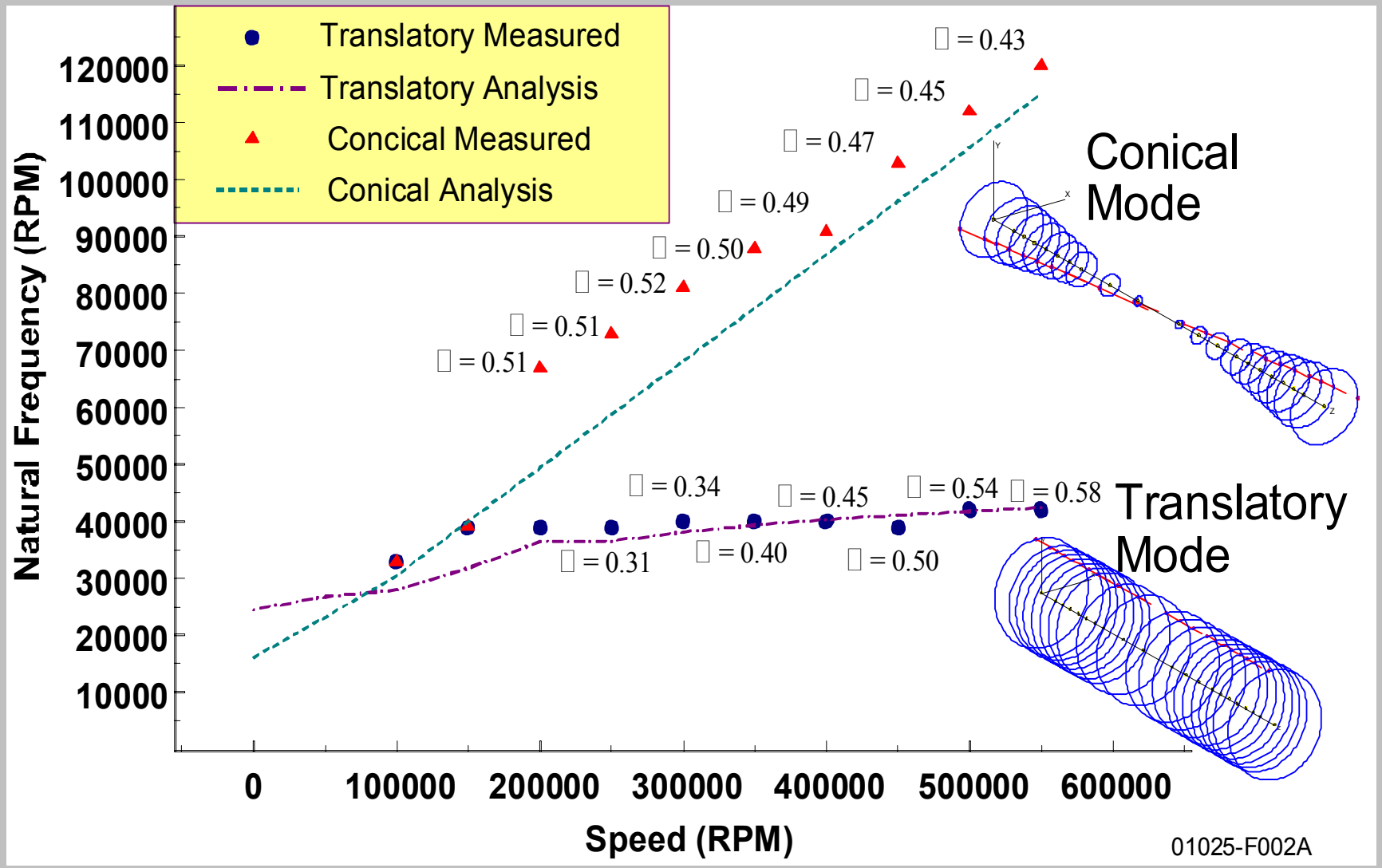
Vertical operation

# Power Loss Comparison

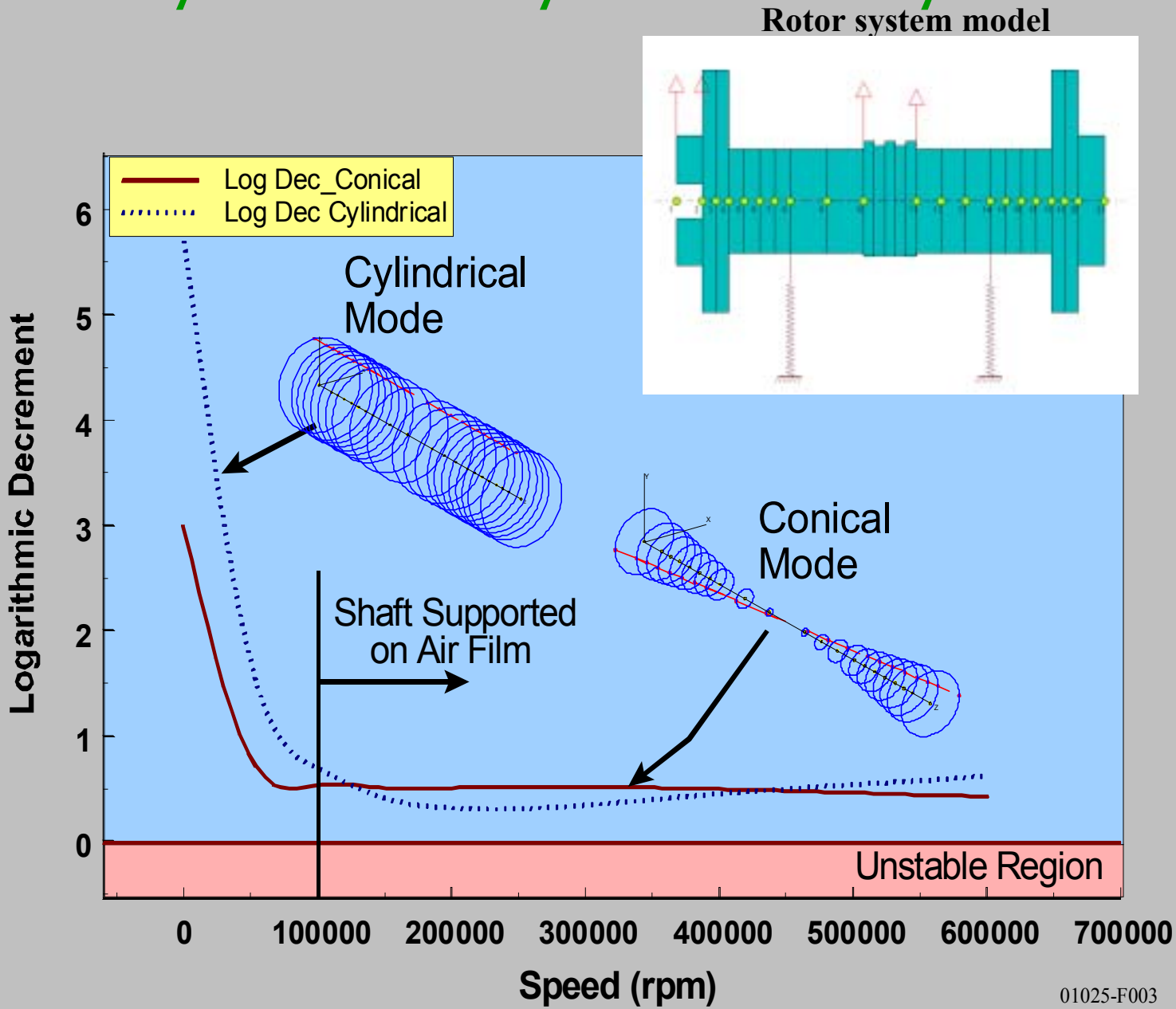



Miniature ball bearing could be used as alternative support bearing, however the preliminary power loss evaluation in these two types of bearings indicated that foil bearings could have power losses 5 times less than that of the ball bearings – Additionally ball bearing are limited in operational temperatures and speeds (DN).

# Rotordynamic Analysis – Whirl speed Map

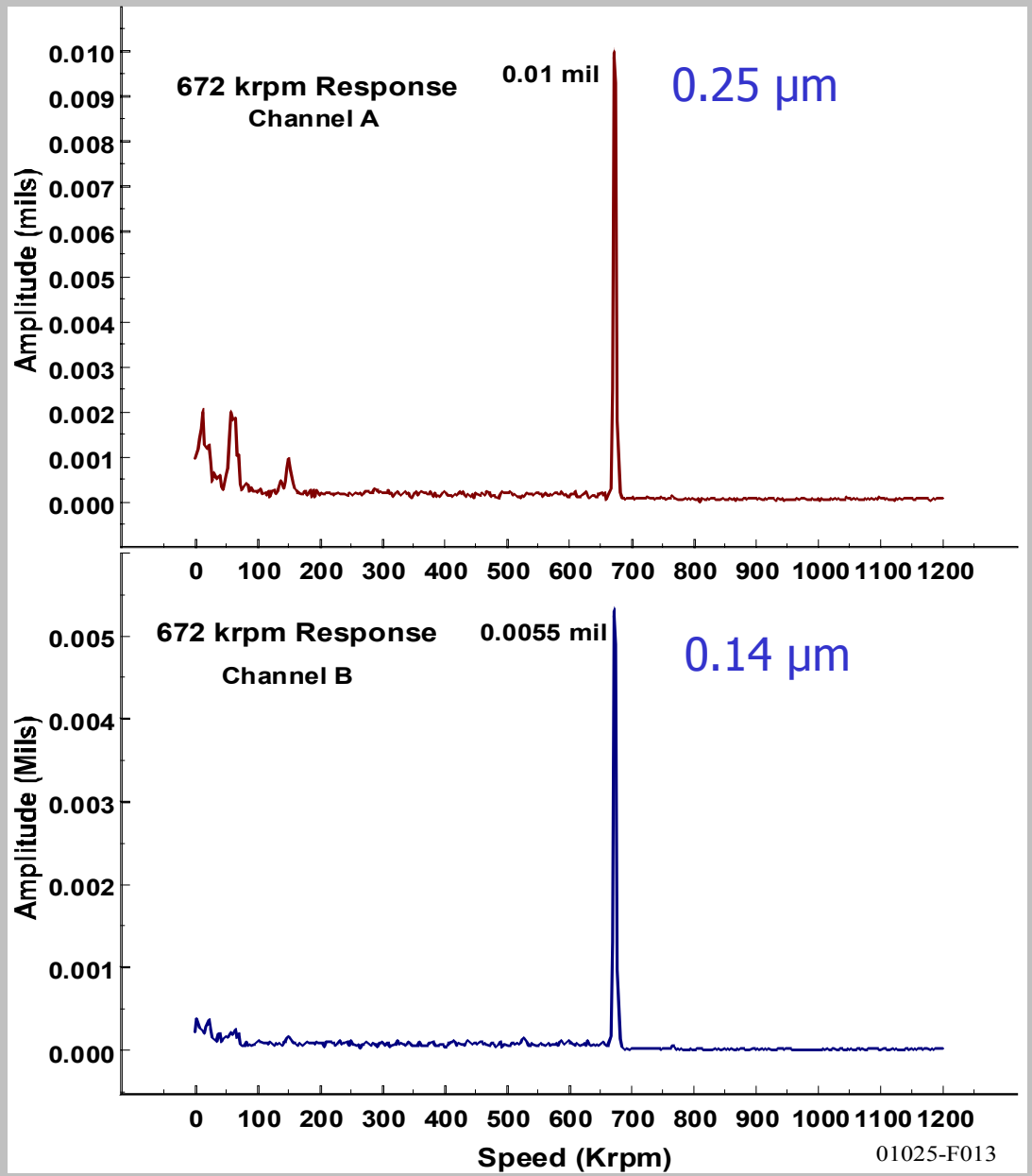


# Rotordynamic Analysis - Stability




01025-F003

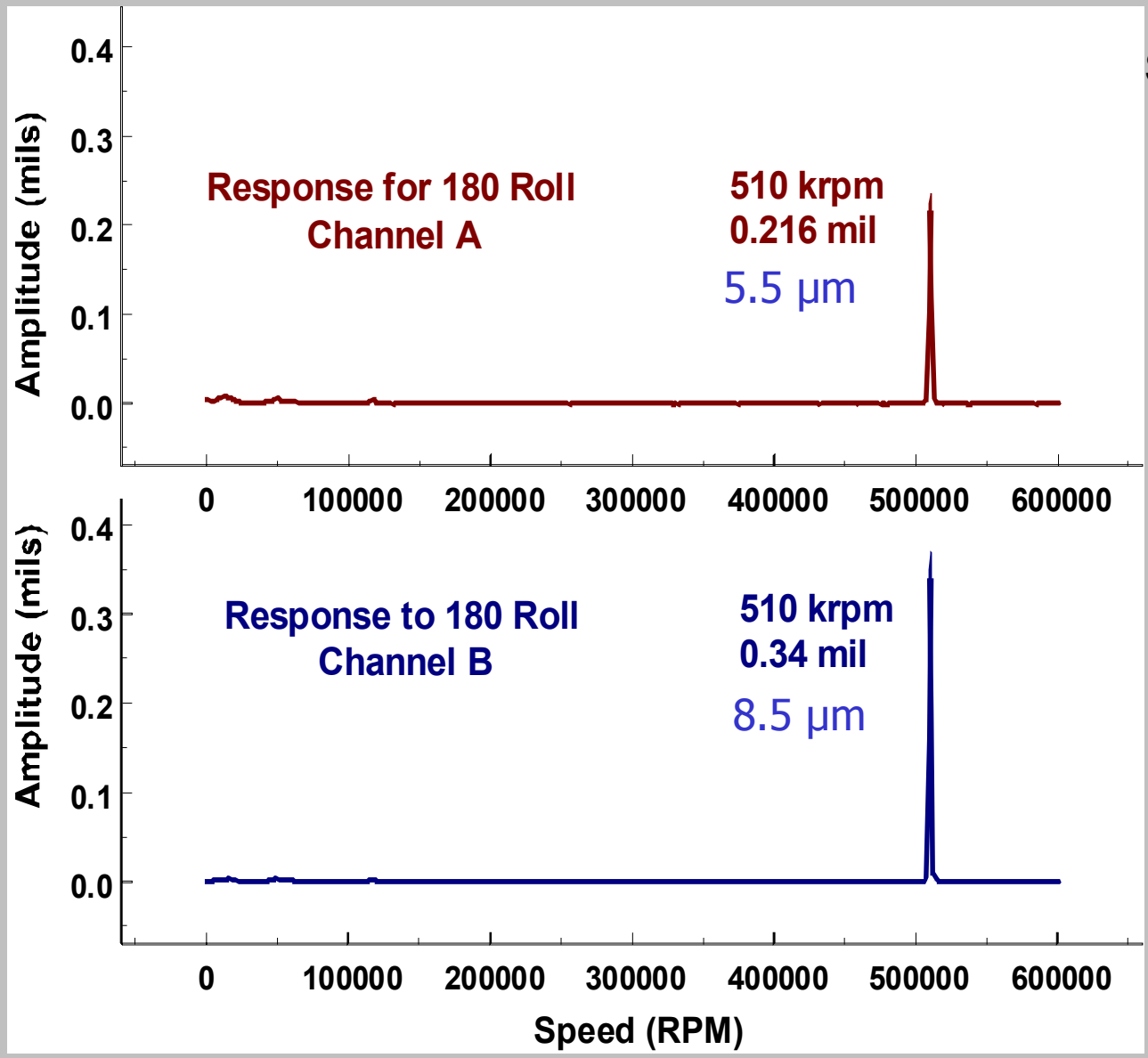
# Test Results



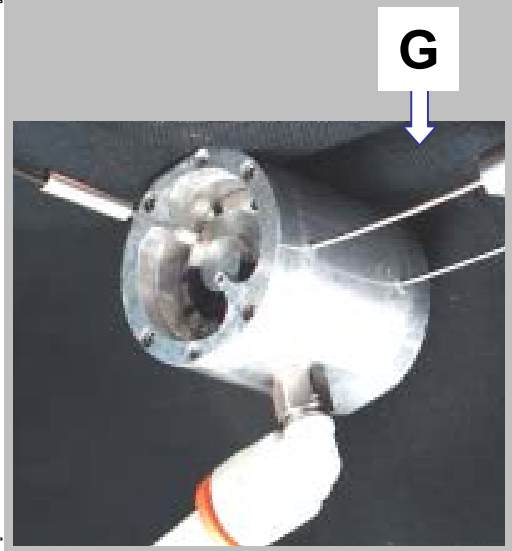

Spectrum for rotor at 672,000

G

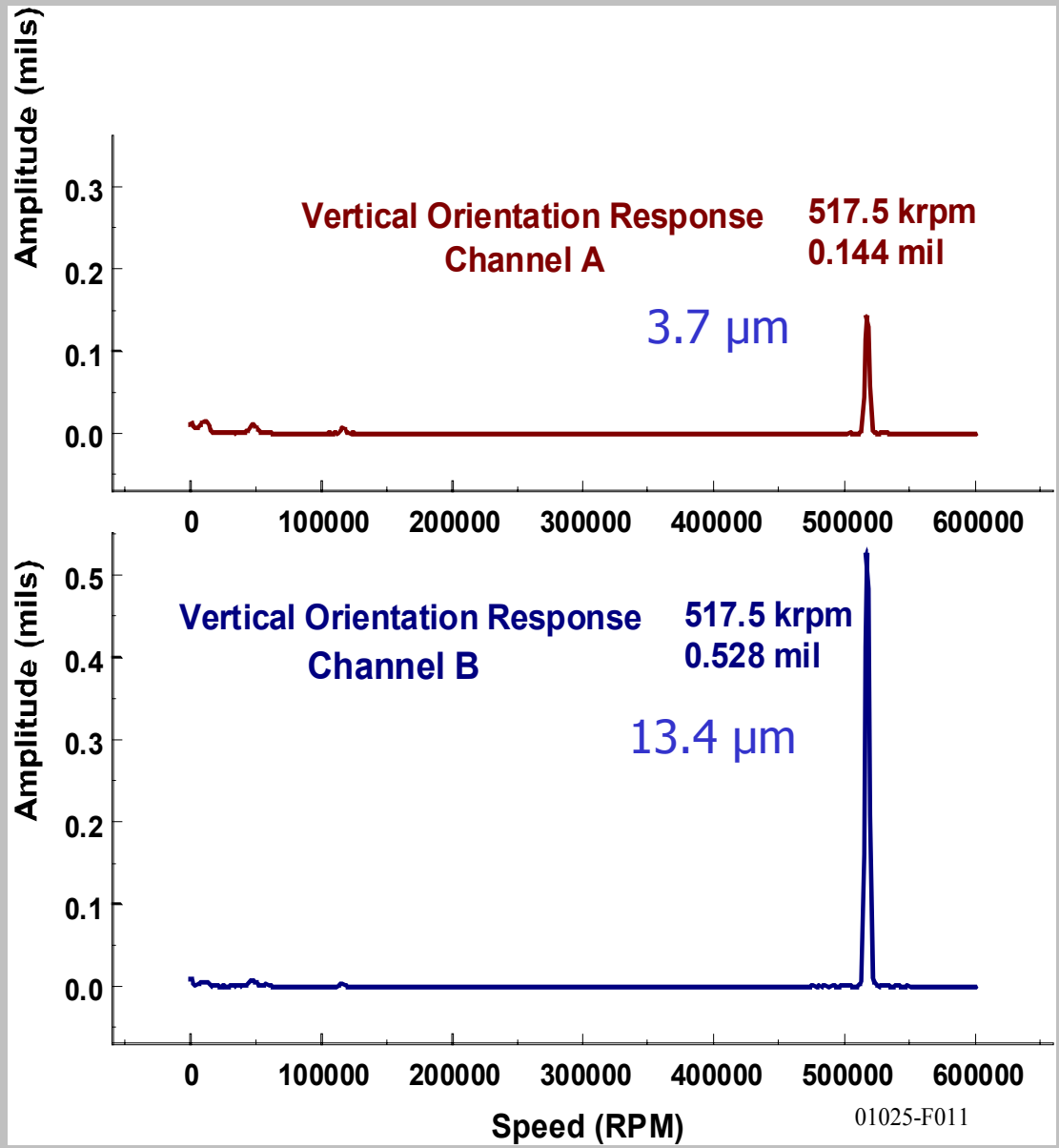
# Test Results (contd)




Spectrum for 180° Roll about spin axis



# Test Results (contd)




Spectrum for vertical operation

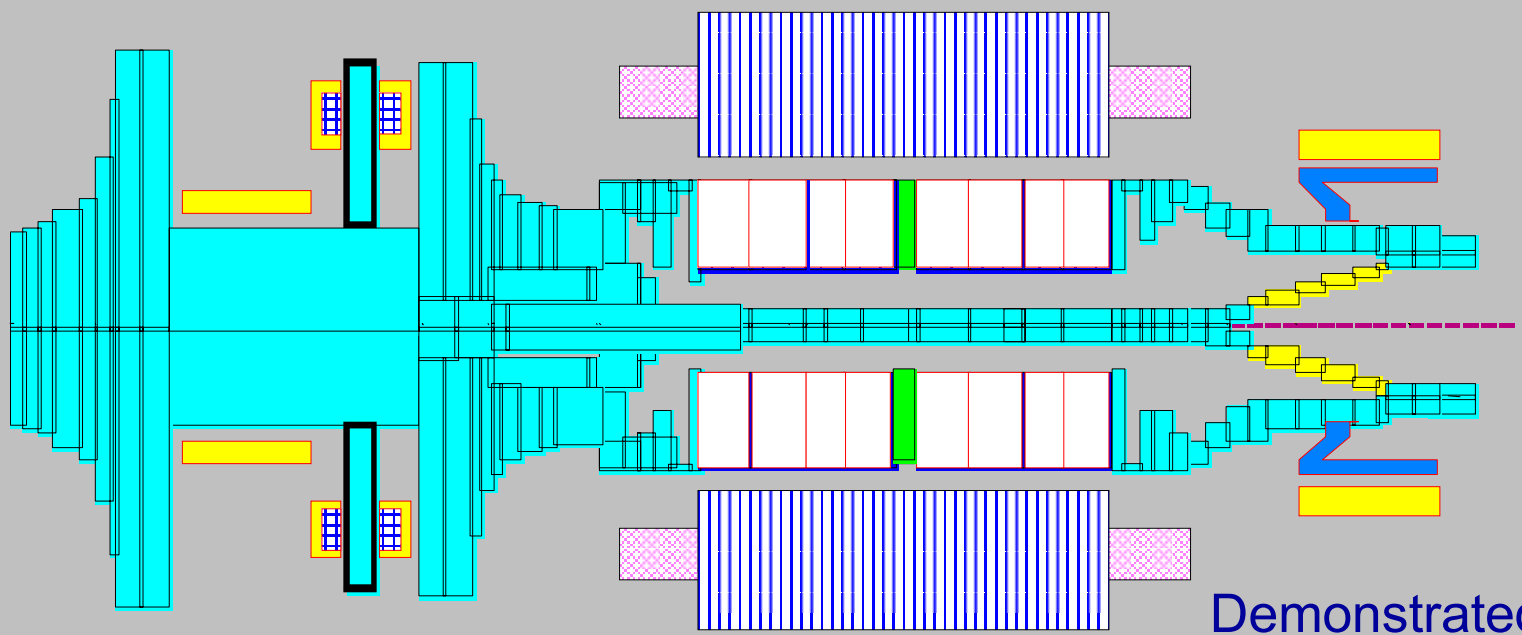
G

# Conclusion-Remarks

MOHAWK INNOVATIVE TECHNOLOGY, INC.

- The successful operation of a mesoscopic scale foil bearing at speeds above 700,000 rpm (4.2 MDN) and a 150 mm foil bearing up to 27,000 rpm (4 MDN) were demonstrated
- Good correlation between prediction and test achieved
- The design know-how from macroscale system design was successfully applied to a mesoscale rotor bearing system
- Foil bearing damping provided stable operation in all orientations
- The results indicate that the potential for developing a 1 million rpm oil-free turbine rotor system is highly feasible
- Specific potential application include turbojets for micro and miniature aerial vehicles to General Aviation

# Micro & Mesoscopic Turbines




Demonstrated

700,000 rpm

All Attitude Operation

Assembly Procedures

Ceramics

# Future Plan

- Alternative bearing design with potential for even higher damping will be installed and tested
- Development of a complete power system with the help of academia and industry
  - Micro combustor
  - Micro compressor
  - Micro turbine
  - Micro generator